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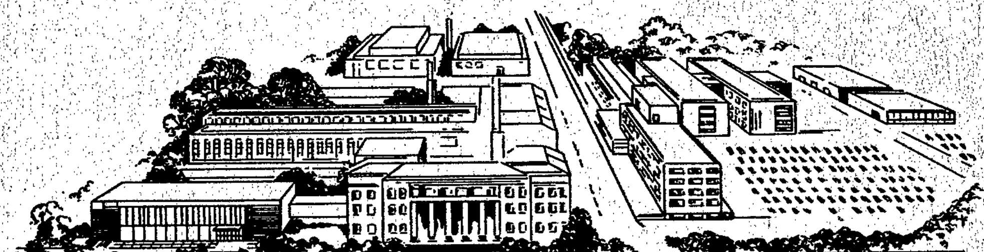
RESEARCH REPORT

DEVELOPMENT OF PROCEDURES FOR
WELDING 2-INCH-THICK
TITANIUM-ALLOY PLATE

to

BUREAU OF NAVAL WEAPONS
DEPARTMENT OF THE NAVY



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BIMONTHLY REPORT

on

DEVELOPMENT OF PROCEDURES FOR WELDING 2-INCH-THICK TITANIUM-ALLOY PLATE

to

BUREAU OF NAVAL WEAPONS
DEPARTMENT OF THE NAVY

February 28, 1961

by

R. L. Koppenhofer, W. J. Lewis, G. E. Faulkner,
and P. J. Rieppel

BATTELLE MEMORIAL INSTITUTE
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DEVELOPMENT OF PROCEDURES FOR WELDING 2-INCH-THICK TITANIUM-ALLOY PLATE

Research is being conducted to develop procedures for welding thick titanium-alloy plates. This research is part of an over-all program to evaluate thick titanium-alloy plate for use in deep-diving submarines. Weldments that have high strength in combination with good ductility and toughness are required for submarine hulls. The specific objectives of the research are to develop procedures to:

(1) Obtain sound ductile welds in 2-inch-thick plate

(2) Obtain joint efficencies of 100 per cent

(3) Obtain satisfactory toughness in weldments.

Prior to this report period, satisfactory welds were made in 2-inch-thick Ti-6Al-4V and Ti-5Al-2.5Sn base plates. Cracking was not obtained in either of these materials using matching filler wire. The welds had joint efficiencies of 100 per cent, tensile elongation lower than that of the base plate in the longitudinal direction, and notch toughness equal to, or greater than, that of the base plate. During this report period, A-70 base plate was received and welds in this plate were evaluated. In addition, joints in Ti-6Al-4V plate welded with A-55 and Ti-5Al-2.5Sn filler wires were evaluated.

This report covers the period from December 30, 1960, to February 28, 1961.

SUMMARY

During the report period, 2-inch-thick A-70 (commercially pure) base plate was received for welding studies. Weld cracking tests were made in this plate using both NRL and Lehigh restraint tests. The properties of welds in 2-inch-thick A-70 base plate also were obtained. All of the welds in A-70 plate were made using A-55 filler wire. In addition, weld joints in the 2-inch-thick Ti-6Al-4V alloy base plate were evaluated. These joints were welded using A-55 and Ti-5Al-2.5Sn alloy filler wires.

No cracking was encountered in either of the cracking tests made on the A-70 base plate. In fact, cracking has not been a problem in welding any of the alloys to date.

The impact properties for the weld made in A-70 base plate using A-55 filler wire were about 5 ft-lb higher than those of the base metal. And, the weld-metal yield strength was about 11,000 psi lower than that of the base plate. These differences are due to the differences in oxygen content of the base plate and weld metal. The base plate contains 0.317 per cent oxygen and the weld metal contains 0.177 per cent oxygen.

In the weld made in Ti-6Al-4V plate with Ti-5Al-2.5Sn filler wire, the notch toughness and yield strength were similar to those of welds made with Ti-6Al-4V filler wire. However, the ductility of the weld made with the Ti-5Al-2.5Sn filler wire was considerably higher than that of the weld made with Ti-6Al-4V filler wire.

In the weld made in Ti-6Al-4V with A-55 filler wire, the notch toughness was considerably better than that of the weld made with matching filler wire. However, the strength of the weld made with A-55 filler wire was low and transverse tension specimens failed in the weld metal at a joint efficiency of only 75 per cent.

A summary of all data obtained so far in the program is shown in Table 1.

WELDING AND TESTING PROCEDURES

All welds were made in an argon-filled chamber with the consumable-electrode welding process. A constant-potential welding-power source connected for reverse polarity was used to supply welding current. All filler wire was 1/16-inch in diameter and was cleaned in acetone prior to welding.

Both NRL and Lehigh specimens were used for restraint tests. A 45-degree double-vee-type joint with a 1/8-inch land was used for all welds in 2-inch-thick, 30-inch-long plates. All joints were cleaned in acetone and pickled in a 40 per cent HNO_3,

TABLE 1. SUMMARY OF ALL DATA OBTAINED TO DATE[a]

Material	Filler Metal	Chemical Composition, per cent									Ultimate Tensile Strength, ksi		Tensile Yield Strength, ksi		Elongation in 2 Inches, per cent		Reduction in Area, per cent		Notch Toughness[b], ft-lb			
		Al	V	Sn	Cr	Fe	C	N	H_2	O_2	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	RT	0 F	−40 F	−80 F
											Ti-6Al-4V											
Base plate	–	6.13	4.16	–	–	0.10	0.01	0.011	0.0056	0.097	132	134.5	115	119	11	8	21	16	21	20	18	16
Filler wire	–	6.78	4.06	–	–	0.11	0.01	0.011	0.0150	0.112	–	–	–	–	–	–	–	–	–	–	–	–
Weld metal	Ti-6Al-4V	6.26	4.16	–	–	0.11	0.02	0.011	0.0046	0.131	144	135	128	(c)	6	(c)	9	(c)	20	17.5	18	16.5
Weld metal	Ti5Al-2.5Sn	5.58	1.22	2.30	–	0.32	0.04	0.011	0.0096	0.143	138.5	137.5	131	(c)	11	(c)	19	(c)	21.5	15	16.5	14
Weld metal	Commercially pure	1.75	1.03	–	–	0.10	0.03	0.014	0.0042	0.133	93	104	83	92	17.5	6	39	29	40	32	26	21.5
											Ti-5Al-2.5Sn											
Base plate	–	5.38	–	2.43	–	0.12	0.07	0.018	0.0027	0.154	136	136.5	128.5	131.5	13	4	25	11	13	10	9	8
Filler wirer	–	6.15	–	2.57	–	0.4	0.01	0.012	0.029	0.100	–	–	–	–	–	–	–	–	–	–	–	–
Weld metal	Ti-5Al-2.5Sn	5.09	–	2.60	–	0.23	0.23	0.015	0.0113	0.084	138	137	125	(c)	8	(c)	12	(c)	18	15	13	11
											Commercially Pure											
Base plate	–	–	–	–	–	0.09	0.03	0.007	0.0073	0.317	97	98	80.5	88	27	25	54	60	12	9.5	12.5	8
Filler wire	–	–	–	–	–	0.12	0.01	0.014	0.0059	0.148	–	–	–	–	–	–	–	–	–	–	–	–
Weld metal	Commercially pure	–	–	–	–	0.11	0.03	0.013	0.0060	0.177	82.5	–	69	–	24	–	44	–	17	13	14	13

(a) All tensile values are averages of two tests.
(b) Base-metal impact properties are averages of two tests for Charpy bars taken in three directions with respect to the rolling direction. Weld-metal impact properties are average of two tests.
(c) Transverse tension specimens failed in the base metal.

2 per cent HF, and 58 per cent water solution prior to welding. The welding conditions used are shown on Table 2.

Standard 0.505-inch-diameter tension specimens and standard Charpy vee-notch impact specimens were used to obtain tensile and impact data. Diamond pyramid hardness data were obtained using a Vickers hardness testing machine with a 10-kg load.

RESULTS AND DISCUSSION

The 2-inch-thick A-70 base plate was received during this report period. A 30-inch-long weld was made in this base plate using filler wire that matched the composition of the base plate. Cracking tests also were made using NRL and Lehigh specimens with matching filler wire. Cracks were not obtained in either of these tests. In fact, cracking has not been encountered in welding any of the alloys.

Welds were evaluated also in the Ti-6Al-4V alloy base plate. These were made with A-55 and Ti-5Al-2.5Sn filler wires. The welds were made to see if impact and/or ductility could be improved without sacrificing other weld properties.

Mechanical Properties

The tensile properties of welds of A-70 base plate made with A-55 filler wire are shown in Table 3. Base-metal properties are included in this table for comparison. The yield strength of the weld metal was 11,000 psi lower than that of the base metal. This difference in yield strength is due to the difference in oxygen content of the base plate and weld metal. The oxygen content of the base plate was 0.317 per cent and that of the weld metal was 0.177 per cent. The notch-toughness properties of welds in A-70 plate are shown in Figure 1a. The weld-metal notch toughness was higher than that of the base plate. Here again, this difference is primarily due to the difference in oxygen content of the weld and base plate.

TABLE 2. WELDING CONDITIONS USED FOR RESTRAINT SPECIMENS AND 30-INCH WELDS

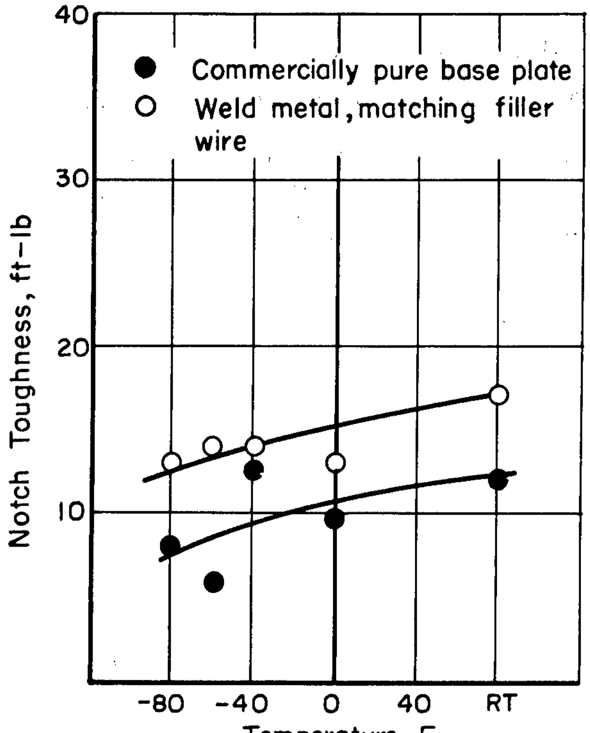
Type of Weld[(a)]	Filler Wire	Weld Travel Speed, ipm	Wire Feed Speed, ipm	Arc Voltage, volts	Weld Current, amperes	Heat Input, joules per inch	Contact-Tube-to-Work Distance, inch	Interpass Temperature, F	Number of Passes
				Ti-6Al-4V Base Plate					
30 inch	Ti-5Al-2.5Sn	15	450	32	340	43,500	3/4	150-200	4
30 inch	Commercially pure	15	450	31	380	47,500	3/4	150-170	4
				Commercially Pure Base Plate					
NRL	Matching	20	450	31	330	31,000	1-1/8	--	1
Lehigh	Matching	20	450	31.5	350	33,000	1	--	1
30 inch	Matching	15	450	31	340	42,000	1	140-170	10

(a) NRL = Naval Research Laboratory Restraint Specimen; Lehigh = Lehigh Restraint Specimen; 30 inch = a 30-inch-long weld in 2-inch-thick plate.

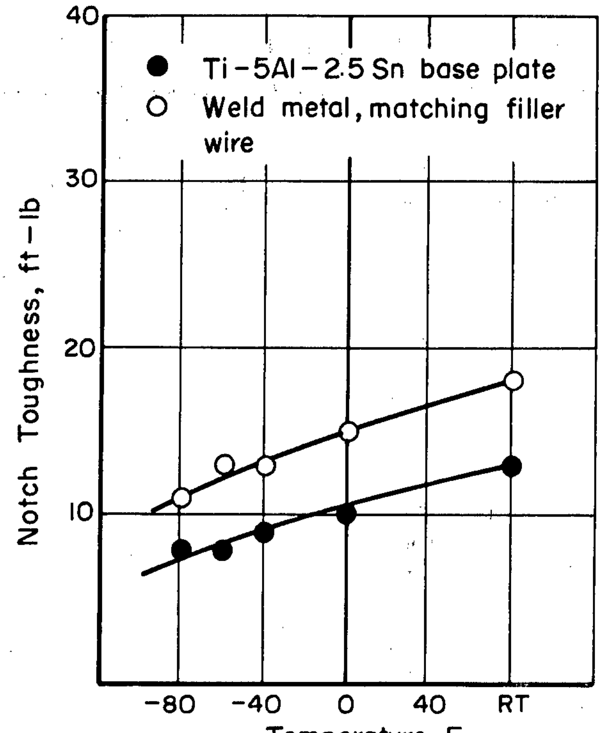
TABLE 3. TENSILE AND BEND PROPERTIES OF WELDS MADE IN Ti-6Al-4V AND A-70[(a)]

Material	Filler-Wire Alloy	Ultimate Tensile Strength, ksi		Tensile Yield Strength[(b)], ksi		Elongation in 2 Inches, per cent		Reduction in Area, per cent	
		Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
				Ti-6Al-4V					
Base metal	--	132	134.5	115	119	11	8	21	16
Weld metal	Matching	144	135	128	(c)	6	(c)	9	(c)
Weld metal	Ti-5Al-2.5Sn	138.5	137.5	131	(c)	11	(c)	19	(c)
Weld metal[(d)]	A-55	93	104	83	92	17.5	6	39	29
				Commercially Pure (A-70)					
Base metal	--	97	98	80.5	88	27	25	54	59
Weld metal	A-55	82.5	--	69.3	--	23.6	--	44	--

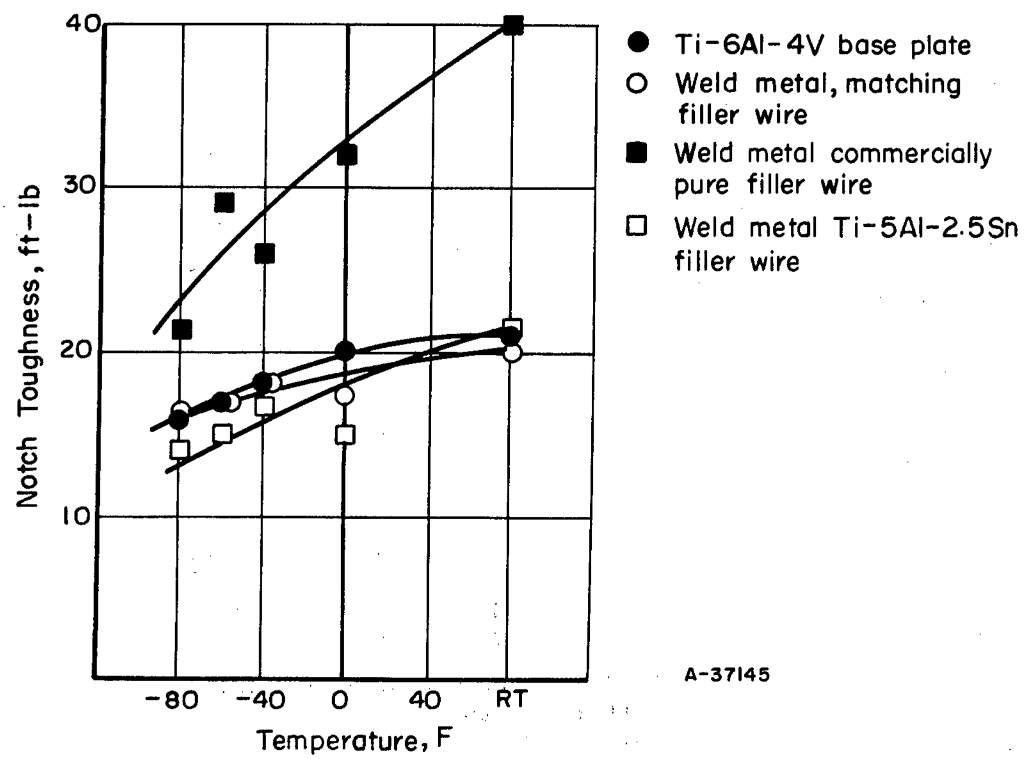
(a) All tensile properties are averages of two tests.
(b) Yield strength taken at 0.2 per cent offset.
(c) Weld-metal transverse specimens failed in the base metal.
(d) Weld-metal transverse specimens failed in the weld metal.



a. Commercially Pure Base Plate



b. Ti-5Al-2.5Sn Base Plate



c. Ti-6Al-4V Base Plate

FIGURE 1. NOTCH TOUGHNESS OF BASE PLATES AND WELD METALS STUDIED TO DATE

The tensile properties of weld metals in Ti-6Al-4V plate made with Ti-5Al-2.5Sn and A-55 filler wires are shown in Table 3. For comparison, the tensile properties of Ti-6Al-4V base plate and the tensile properties of the weld in Ti-6Al-4V base plate made with matching filler are included. The yield strength of the weld made with Ti-5Al-2.5Sn filler compared with the yield strength of the weld made with Ti-6Al-4V filler. However, the ductility of the Ti-5Al-2.5Sn weld (11 per cent) was considerably higher than that of the Ti-6Al-4V weld (6 per cent). The yield strength of the weld made in Ti-6Al-4V base plate with A-55 filler wire was very low compared with the other welds in Ti-6Al-4V plate. In fact, transverse tension specimens failed in the weld at about 75 per cent joint efficiency.

The notch toughness of welds in Ti-6Al-4V made with Ti-5Al-2.5Sn and A-55 filler wires is shown in Figure 1c. The notch toughness of the weld made with A-55 filler is the highest obtained so far. The impact properties of welds made with Ti-5Al-2.5Sn filler wire were about the same as welds made with Ti-6Al-4V filler wire.

Chemical Analysis

Chemical analysis of the weld in Ti-5Al-2.5Sn made with matching filler wire and of welds made during this report period are given in Table 4. Base-metal and filler-wire analyses are given for comparision. Chemical analyses were used to obtain data on all elements except hydrogen and oxygen. Vacuum-fusion analyses were made to obtain hydrogen and oxygen contents.

All of the analyses are within the expected limits with the exception of the hydrogen content of the Ti-5Al-2.5Sn filler wire (0.029 per cent) and the carbon content of the Ti-5Al-2.5Sn weld metal (0.23 per cent). Both of these results appear high and additional analyses are being made.

TABLE 4. CHEMICAL AND VACUUM-FUSION ANALYSES OF BASE PLATE, FILLER WIRE, AND WELD METALS

Material	Filler Wire	Composition, per cent								
		Al	V	Sn	Cr	Fe	C	N	H_2	O_2
				Ti-6Al-4V						
Base plate	--	6.13	4.16	--	--	0.10	0.01	0.011	0.0056	0.097
Filler wire	--	6.78	4.06	--	--	0.11	0.01	0.011	0.015	0.112
Weld metal	Ti-5Al-2.5Sn	5.58	1.22	2.30	--	0.32	0.04	0.011	0.0096	0.1430
Weld metal	Commercially pure	1.75	1.03	--	--	0.10	0.03	0.014	0.0042	0.1330
				Ti-5Al-2.5Sn						
Base plate	--	5.38	--	2.43	--	0.12	0.07	0.018	0.0027	0.154
Filler wire	--	6.15	--	2.57	--	0.40	0.01	0.012	0.0314	0.1000
Filler wire	(Recheck analysis)	5.37	--	2.58	--	0.43	0.03	0.014	0.0266	--
Weld metal	Ti-5Al-2.5Sn	5.09	--	2.60	--	0.23	0.26	0.015	0.0113	0.084
Weld metal	(Recheck analysis)	--	--	--	--	--	0.21	--	--	--
				Commercially Pure						
Base plate	--	--	--	--	--	0.09	0.03	0.007	0.0073	0.317
Filler wire	--	--	--	--	--	0.12	0.01	0.014	0.0059	0.148
Weld metal	Commercially pure	--	--	--	--	0.11	0.03	0.013	0.0060	0.177

The weld metal deposited in Ti-6Al-4V alloy base plate with Ti-5Al-2.5Sn filler wire had 5.58 per cent aluminum, 1.22 per cent vanadium, and 2.30 per cent tin. These changes in composition as compared with those of the weld made using Ti-6Al-4V filler wire were found to increase the tensile elongation and give about the same impact properties.

The weld metal deposited in Ti-6Al-4V alloy base plate with commercially pure filler wire had 1.75 per cent aluminum and 1.03 per cent vanadium. This relatively low alloy content resulted in weld metal with considerably higher impact properties than any of the welds made to date. However, transverse tension specimens showed only a 75 per cent joint efficiency.

Metallographic and Hardness Studies

Metallographic studies were made on base plates, weld metals, and heat-affected zones of joints made to date.

Figures 2, 3, and 4 show, respectively, the base plate microstructure for commercially pure, Ti-5Al-2.5Sn and Ti-6Al-4V alloy base plates. Complete mill-process history has not as yet been received from the producers of the base-plate materials, but on the basis of the microstructure we estimated the working and annealing ranges.

The commercially pure base plate (Figure 2) has an equiaxed small grain structure similar to that obtained by working and annealing in the alpha field. The weld-metal and heat-affected-zone structures are shown in Figures 5 and 6 for comparison.

The Ti-5Al-2.5Sn alloy base plate (Figure 3) consists of an annealed structure probably worked in the beta field. Figures 7 and 8 are, respectively, the weld metal and heat-affected-zone structures of the weld made using Ti-5Al-2.5Sn base metal and filler wire.

The Ti-6Al-4V base plate (Figure 8) has a coarse grain structure consisting of transformed beta. This plate apparently was worked at temperatures in the beta field.

Figures 9 and 10 show, respectively, the weld metal and heat-affected zone for the weld made using Ti-6Al-4V base plate and filler wires. Figures 11 and 12 are microstructures of the weld metal obtained using A-55 and Ti-5Al-2.5Sn filler wires, respectively, in Ti-6Al-4V base plate.

Vickers diamond pyramid hardness traverses were made across the weld in restraint specimens that were sectioned for metallographic examination. Hardness impressions were taken at 0.030-inch intervals for the Ti-6Al-4V and Ti-5Al-2.5Sn alloys and at 0.050-inch intervals for the commercially pure titanium. Table 5 is a summary of these data.

100X N76495

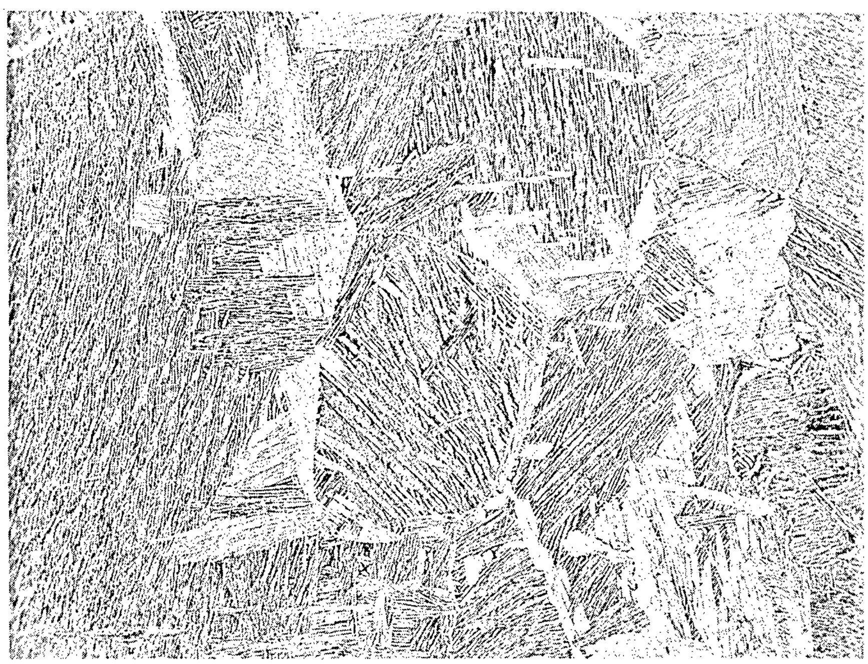
Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 2. MICROSTRUCTURE OF COMMERCIALLY PURE BASE PLATE

100X N76498

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

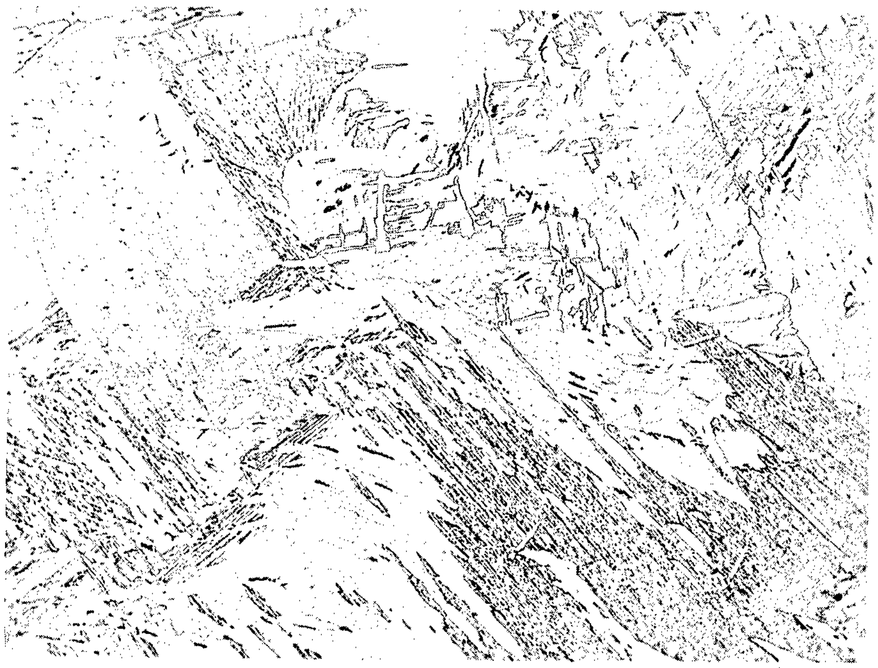
FIGURE 3. MICROSTRUCTURE OF Ti-5Al-2.5Sn BASE METAL



100X N75971

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 4. MICROSTRUCTURE OF Ti-6Al-4V BASE PLATE



100X N76497

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 5. WELD-METAL STRUCTURE OBTAINED BY DEPOSITING COMMERCIALLY PURE FILLER WIRE IN COMMERCIALLY PURE BASE PLATE

100X N76496

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 6. WELD HEAT-AFFECTED-ZONE STRUCTURE FOR COMMERCIALLY PURE BASE PLATE

100X N76500

Etchant 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 7. WELD-METAL STRUCTURE OBTAINED BY DEPOSITING Ti-5Al-2.5Sn FILLER WIRE IN Ti-5Al-2.5Sn BASE PLATE

100X N76499

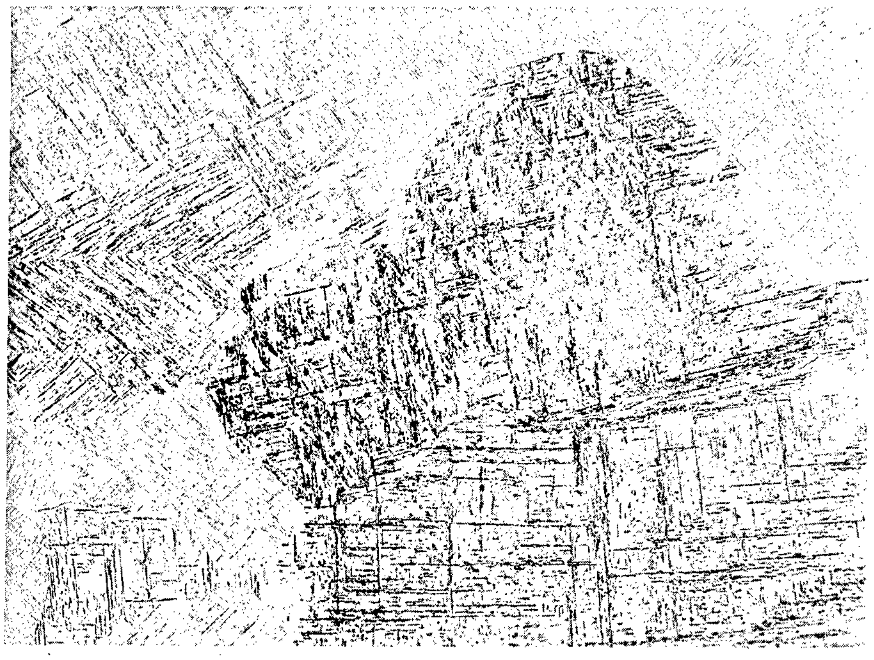
Etchant 1.5HF, 3.5 HNO_3, Balance H_2O

FIGURE 8. WELD HEAT-AFFECTED-ZONE STRUCTURE FOR Ti-5Al-2.5Sn BASE PLATE

100X N75972

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

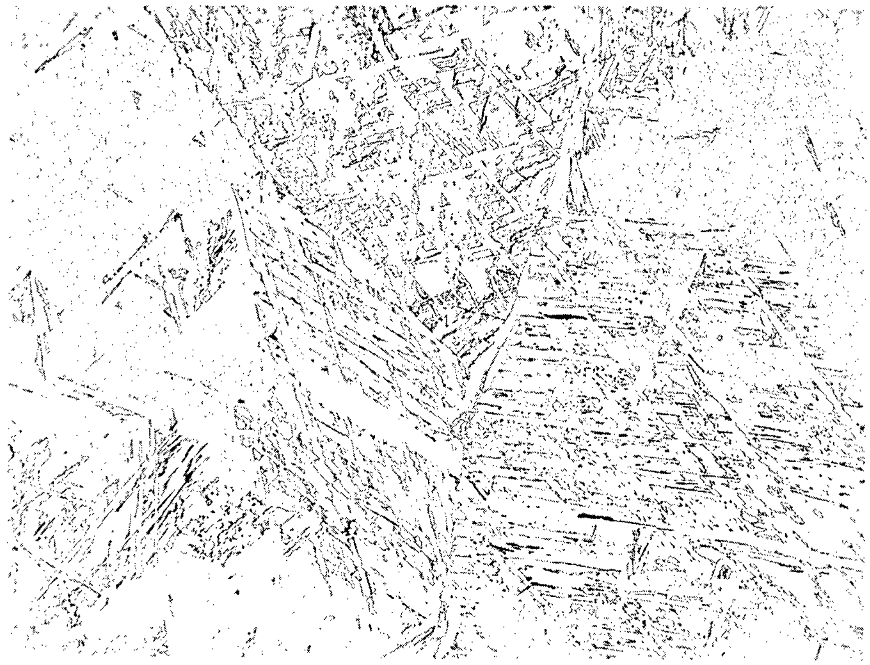
FIGURE 9. WELD-METAL STRUCTURE OBTAINED BY DEPOSITING Ti-6Al-4V FILLER WIRE IN Ti-6Al-4V BASE PLATE



100X N76501

Etchant: 1.5HF, 3.5 HNO_3, Balance H_2O

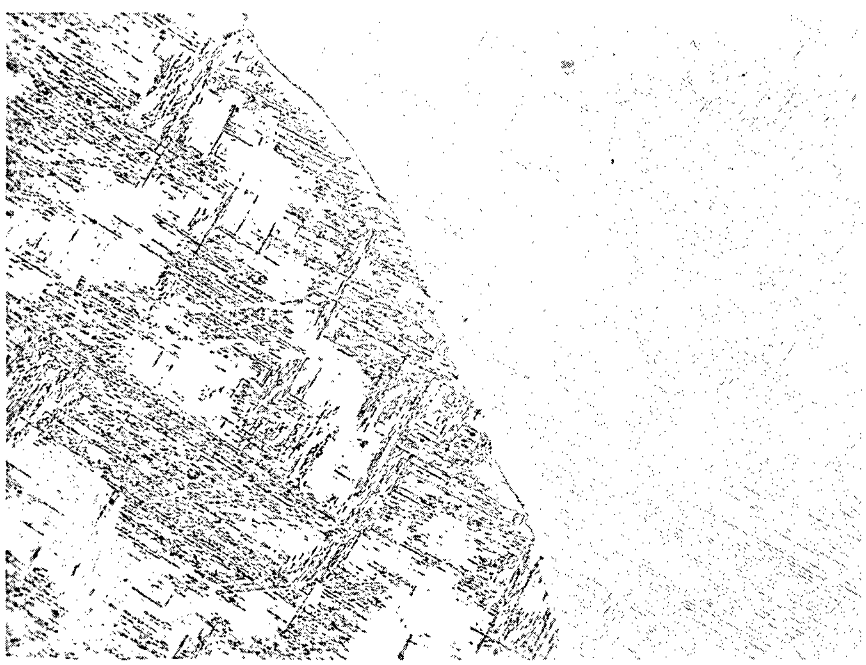
FIGURE 10. WELD HEAT-AFFECTED-ZONE STRUCTURE FOR Ti-6Al-4V BASE PLATE



100X N76504

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 11. WELD-METAL STRUCTURE OBTAINED BY DEPOSITING COMMERCIALLY PURE FILLER WIRE IN Ti-6Al-4V BASE PLATE



100X N76502

Etchant: 1.5 HF, 3.5 HNO_3, Balance H_2O

FIGURE 12. WELD-METAL STRUCTURE OBTAINED BY DEPOSITING Ti-5Al-2.5Sn FILLER WIRE IN Ti-6Al-4V BASE PLATE

TABLE 5. SUMMARY OF HARDNESS DATA OBTAINED TO DATE

		Hardness, Vickers Diamond Pyramid Hardness Numbers					
		Base Metal		Heat-Affected Zone		Weld Metal	
Type Weld[a]	Filler Wire	Range	Average	Range	Average	Range	Average
		Ti-6Al-4V					
NRL	Matching	303 to 359	331	333 to 370	346	322 to 365	352
		Ti-5Al-2.5Sn					
NRL	Matching	307 to 358	333	333 to 359	346	337 to 368	353
		Commercially Pure					
NRL	Matching	245 to 272	254	243 to 291	262	210 to 258	224

(a) NRL = Naval Research Laboratory Restraint Specimen.

CONCLUSIONS

The following conclusions can be drawn from results obtained to date:

(1) Welds made to date using Ti-6Al-4V, Ti-5Al-2.5Sn and commercially pure base plates indicate that cracking will not be a problem with these alloys.

(2) The use of commercially pure filler wire deposited in Ti-6Al-4V base plate produced good weld-metal impact properties, but only a 75 per cent joint efficiency.

(3) Ti-5Al-2.5Sn filler wire deposited in Ti-6Al-4V base plate produced weld metal with about the same impact properties and strength but better ductility than of the weld made in this base plate using Ti-6Al-4V filler wire.

(4) Commercially pure filler wire deposited in commercially pure base plate produced a weld with higher impact properties and lower strength than that of the base metal.

FUTURE WORK

In the future, welding tests will be continued on the three base plates received to date in an effort to evaluate different welding conditions. Work will begin on the Ti-13V-11Cr-3Al alloy when the base-plate material is received.

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Data are recorded in Battelle Laboratory Record Book 17387, pages 1 through 80.

RLK:WJL:GEF:PJR/nb